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R. Vogt, C. Lourenco, H. Woehri

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J/ψ production and absorption in $p + A$ and d+Au collisions

R. Vogt[1,2], C. Lourenço[3] and H. K. Wöhri[3,4]

[1] *Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
[2] *University of California, Davis, CA 95616, USA*
[3] *CERN, CH-1211 Geneva 23, Switzerland*
[4] *LIP, Av. Elias Garcia, 14-1, 1000-149 Lisboa, Portugal*

Abstract

The level of "anomalous" charmonium suppression in high-energy heavy-ion collisions and its interpretation as a signal of quark-gluon plasma formation requires a robust understanding of charmonium production and absorption in proton-nucleus collisions. In a previous study we have shown that, contrary to common belief, the so-called J/ψ "absorption cross section", $\sigma_{\rm abs}^{J/\psi}$, is not a "universal constant" but, rather, an effective parameter that depends very significantly on the charmonium rapidity and on the collision energy. Here we present ugraded Glauber calculations with the EPS09 parameterization of nuclear modifications of the parton densities. We confirm that the effective "absorption cross section" depends on the J/ψ kinematics and the collision energy. We also make further steps towards understanding the physics of the mechanisms behind the observed "cold nuclear matter" effects.

Keywords: quarkonium, cold nuclear matter

Understanding cold nuclear matter (CNM) effects on quarkonium begins with quarkonium production in pp collisions. We calculate quarkonium production within the context of the phenomenologically successful color evaporation model (CEM) [1]. In the CEM, the quarkonium production cross section is some fraction F_C of all $Q\overline{Q}$ pairs below the $H\overline{H}$ threshold where H is the lowest mass heavy-flavor hadron. Thus the CEM cross section is the $Q\overline{Q}$ production cross section with a cut on the pair mass but without any constraints on the color or spin of the final state. The produced $Q\overline{Q}$ pair then neutralizes its color by interaction with the collision-induced color field. The yield of all quarkonium states may be only a small fraction of the total $Q\overline{Q}$ cross section below $2m_H$.

The fraction F_C must be universal so that, once it is fixed by data, the quarkonium production ratios should be constant as a function of $\sqrt{s}$, y and p_T. The actual value of F_C depends on the heavy quark mass, m_Q, the scale, μ^2, the parton densities, $f_i^A(x, \mu^2)$ and the order of the calculation. The quarkonium production ratios are indeed consistent with being independent of kinematics, as expected by the model [2, 3].

The leading order calculation is insufficient to describe high p_T quarkonium production since the $Q\overline{Q}$ pair p_T is zero at LO. Therefore, the CEM was taken to NLO [2, 4] (LO in the p_T distribution) using the exclusive $Q\overline{Q}$ hadroproduction code of Ref. [5]. The results give a good description of the quarkonium p_T distributions at the Tevatron [4] and RHIC, see Fig. 1, as well as preliminary results on the p_T dependence of J/ψ and Υ production in 7 TeV collisions at the LHC [7]. In the exclusive NLO calculation [5], the scale is $\mu^2 \propto m_T^2 = m_Q^2 + p_T^2$ where p_T is the transverse momentum of the $Q\overline{Q}$ pair, $p_T^2 = 0.5(p_{T_Q}^2 + p_{T_{\overline{Q}}}^2)$.

We use parton densities and parameters that approximately agree with the $Q\overline{Q}$ total cross section data to determine F_C for J/ψ and Υ production. Analysis shows that the charm total cross section results favor low charm quark masses combined with relatively high factorization and renormalization scales [8]. Using the CTEQ6M parton densities, the best results were obtained with $m_c = 1.2$ GeV and $\mu_F = \mu_R = 2m_T$, as also used in Refs. [2, 4].

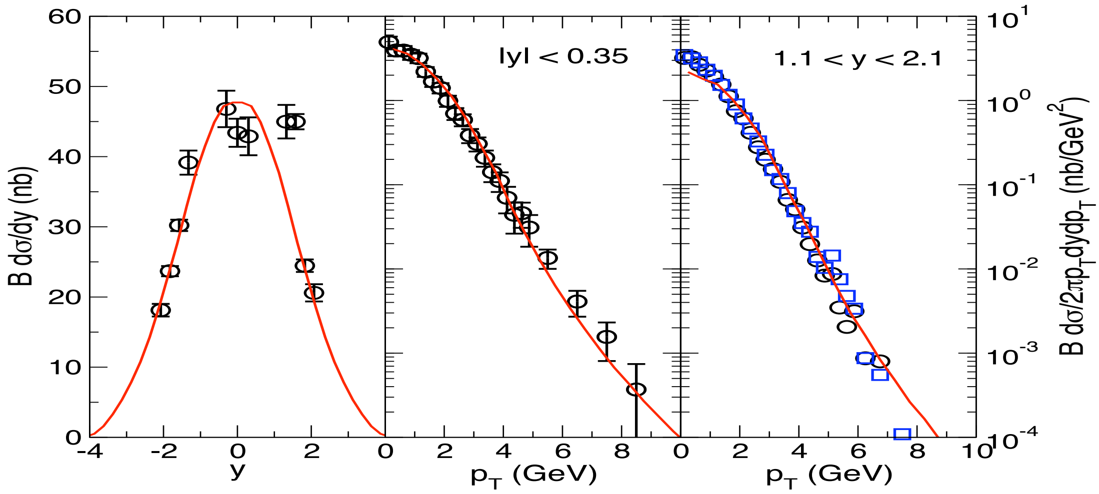

Figure 1: PHENIX pp measurements [6] compared to a CEM calculation at $\sqrt{s} = 200$ GeV. The J/ψ rapidity distribution (left) and transverse momentum distributions at midrapidity (center) and in the muon arms (right). The results are calculated with CTEQ6M, $(m, \mu_F/m_T, \mu_R/m_T) = (1.2, 2, 2)$, $\langle k_T^2 \rangle = 1.38$ GeV^2.

Since the CEM provides a good description of quarkonium hadroproduction, we use it to study CNM effects on quarkonium. The most prominent effects studied so far are initial-state effects on the parton densities (shadowing); initial- (and/or final-) state energy loss; final-state absorption by nucleons; and production from intrinsic $Q\overline{Q}$ Fock states of the nucleons [9, 10].

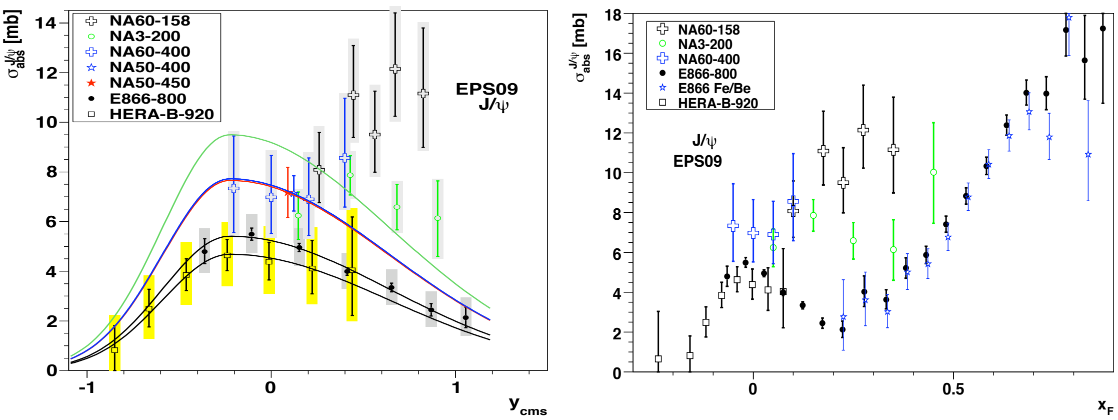

Figure 2: Left: Dependence of $\sigma_{\rm abs}^{J/\psi}$ on $y_{\rm cms}$ for all available data sets including EPS09 shadowing [12]. The shape of the curves is fixed by the E866 and HERA-B data. Right: The x_F dependence of $\sigma_{\rm abs}^{J/\psi}$ for incident fixed-target energies from 158, 200, 400, 450, 800, 920 GeV using the EPS09 parameterization.

The effective J/ψ absorption cross section at $x_F \sim 0$ is seen to decrease with energy, regardless of the chosen shadowing parameterization [11]. A recent result with the EPS09 shadowing parameterization [12], is shown on the left-hand side of Fig. 2. Further away from midrapidity, the effective absorption cross section rises with the rapidity or x_F of the observed J/ψ, shown on the right-hand side of Fig. 2. The rise begins closer to midrapidity at lower energies, corresponding to large projectile momentum fractions, x_1, and not indicative of initial-state shadowing which depends on the target momentum fraction x_2. Thus the increase in the effective absorption cross section may be due to initial-state energy loss. At lower $\sqrt{s}$, the large x_1 regime ($x_1 > 0.1$) begins closer to midrapidity.

To quantify initial-state energy loss, we turn to Drell-Yan production, $q\overline{q} \to \gamma^*$ at leading order and $q\overline{q} \to \gamma^* g$, $qg \to q\gamma^*$ at next-to-leading order, a cleaner environment for studying quark energy loss. There is no possibility of final-state loss since the produced lepton pair does not interact with the medium. Initial-state energy loss is usually assumed to be due to multiple-scattering by the projectile parton it moves through the nucleus. Both the quarks and gluons can scatter elastically and lose energy before the hard scattering. The projectile parton momentum fraction, x_1, is depeleted by an amount Δx_1, becoming $x_1' = x_1 - \Delta x_1$. The shifted value, x_1', enters the partonic cross sections but the parton distributions are evaluated at the initial x_1.

We calculate the mass and rapidity/x_F dependence of Drell-Yan production at next-to-leading order. The NNLO contributions [13] are only a small addition (a few percent) to the NLO correction. The theoretical K factors are close to unity [14, 15]. The left-hand side of Fig. 3 compares the NLO cross section, with an experimental K factor of 1.124 ± 0.007 (stat) ± 0.073 (syst), to the E866 Drell-Yan data in fixed-target pp collisions with a beam momentum of 800 GeV [16]. The individual data points agree with the NLO calculation within a 2σ uncertainty band, given by the data. Thus our calculations give a good description of the available Drell-Yan pp data and can then be used to extract the initial-state parton energy loss from proton-nucleus data.

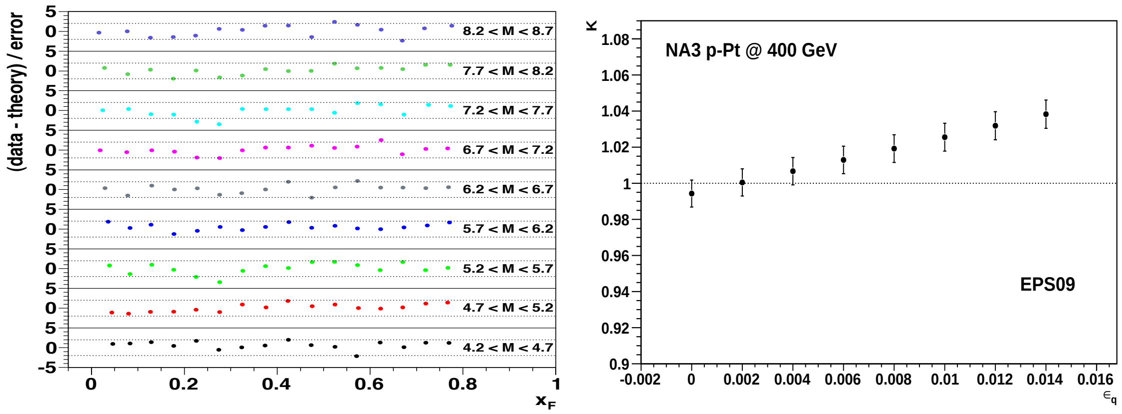

Figure 3: Left: Difference between the measured Drell-Yan cross section and the NLO calculations in the same mass bin. Right: The K factors found in comparison to the data with various values of the energy loss parameter ϵ_q.

We begin with the assumption that the fractional energy loss is dependent on the number of collisions the projectile parton makes as it traverses the nucleus,

$$x_1 = \frac{x_1'}{(1-\epsilon_i)^{N_{\rm coll}-1}} \tag{1}$$

where ϵ_i is a parameter that can be tuned to the data and $N_{\rm coll} \propto A^{1/3}$ in pA collisions. We assume that ϵ_q and ϵ_g are related by the Casimir factors, $\epsilon_g = (9/4)\epsilon_q$.

NA3 measured the double-differential Drell-Yan cross section in p+Pt collisions at $E_{\rm lab} = 400$ GeV [17]. The NA3 x_F distributions were analyzed in 20 mass intervals in the range $4.6 < M < 8.4$ GeV. We can extract the level of initial-state energy loss by fitting the NLO calculations to these data with the K factor and ϵ_q as free parameters. In this case, the calculations include initial-state energy loss as well as the nuclear modifications of the parton distribution functions, employing the EPS09 parameterization[1].

The right-hand side of Fig. 3 shows that the K factor increases with ϵ_q while the quality of the fit systematically degrades. Given that the best fit is obtained with $\epsilon_q = 0$, we can set an upper limit on ϵ_q compatible with the high-precision NA3 data. To 99 % confidence level, ϵ_q is smaller than 0.0018. We have repeated the fits with standard proton PDFs. The results are very similar, giving an upper limit on ϵ_q of 0.002 at 99 % confidence level.

[1]The NA3 data were not used in the EPS09 global analysis [12].

The quark shadowing effect is rather weak and, more importantly, practically independent of x_F in the 400 GeV NA3 data. Thus the difference between the pp cross section calculated with the free proton PDFs and PDFs modified by the EPS09 parameterization in p+Pt interactions at 400 GeV can be absorbed into the K factor. The 400 GeV NA3 data is therefore well suited for the study of initial-state energy loss.

We may also compare to the Drell-Yan data measured at 800 GeV by the E866 [18] (W/Be and Fe/Be cross section ratios for $4 < M < 8$ GeV) and E772 [19] (W/D and Fe/D cross section ratios for $4 < M < 9$ GeV and $M > 11$ GeV) experiments. Since these data were used in the global EPS09 analyses, we cannot employ them to extract the initial-state energy loss parameters. We can, however, check whether or not these ratios are compatible with calculations using the results extracted from the NA3 data. At this energy, the cross section ratios are no longer independent of x_F. While the calculated ratios do not require initial-state energy loss in order to agree with the data, they are also compatible with the small maximal level of energy loss extracted from NA3.

Using the ϵ_q obtained from the Drell-Yan data, we can see if quarkonium production, primarily through gg initial states, is compatible with such a small initial-state energy loss. If so, the rise in $\sigma_{\rm abs}^{J/\psi}$ at large x_F, seen on the right-hand side of Fig. 2, could be attributed to initial-state energy loss, resulting in a small, kinematics independent absorption cross section in the forward region. However, $\epsilon_q = 0.002$ and $\epsilon_g = (9/4)\epsilon_q$ are insufficient to account for the effect. If we assume the J/ψ is subject to final-state energy loss with the same general behavior as in Eq. (1), an order of magnitude larger ϵ_q (~ 0.020) is needed to describe the data.

To confirm the importance of final-state energy loss on J/ψ production, we can use open charm production as an independent check on our conclusions about initial-state energy loss in the Drell-Yan process since open charm also does not suffer from final-state absorption. We will test our Drell-Yan results against other available data as well as with other parameterizations of the energy loss. We also plan to take the formation times of the quarkonium states into account to study J/ψ absorption.

Acknowledgments

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